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by

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A DYNAMIC AIRCRAFT SIMULATOR FOR STUDY OF HUMAN RESPONSE CHARACTERISTICS

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Introduction

A dynamic high speed jet aircraft simulator is described. This simulator is intended for use in psychological experiments designed to determine the transfer characteristics of a pilot under simulated flying conditions. A two gun scope in the cockpit presents an indication of the roll and bank angles of the aircraft and the position of a target. The target can be made to follow any prescribed course by means of an electronic function generator, or to move in a random way by a filtered white noise source. Potentiometers geared to the stick and rudder feed voltages into an analog computer which solves the equations of motion of the aircraft and the components of target lead angle. The computer employs negative feedback d-c amplifiers and servo-multiplier techniques.

The work described in this paper was sponsored jointly by the Aircraft Laboratory and the Aeromedical Laboratory of Wright Air Development Center, Wright-Patterson Air Force Base, Dayton, Ohio.

The Closed Loop System

Figure No. 1 shows a block diagram of the simulator and the equations that are mechanized therein. The first seven equations solve the motion of the aircraft in response to elevator, aileron, and rudder motions. The next set of equations govern target motion relative to the airplane. These equations are based upon our own aircraft pursuing the target at a constant speed and at a constant range. In addition to this, certain other simplifying assumptions were made in the derivation of these equations. The major simplification involves small angle assumptions for the following variables:

1. dive angle, δ
2. angle of attack, α
3. angle of skid, ψ
4. target position angles, τ_A & τ_E

Small angle assumptions are based upon the physical consideration of a jet aircraft flying at high speed. The validity of the simplifications was verified by the close agreement between simulator solutions and flight test data. An example of this will be given later.

It should be noted that some of the coefficients in the equations have dimensions. The first three equations are based upon the moment equations of the physical system and provide a solution for the angular rates about the three axes with the aircraft at the origin. There are three force equations which pertain to the physical system, but with airspeed assumed constant one of them can be neglected. The remaining two force equations are then

solved for angle of skid ψ and the attack angle α. Knowing the angular rates, the bank angle β and dive angle δ can be solved as indicated.

The target position angles τ_A and τ_E (azimuth and elevation) are based upon the solution of the first five equations of airplane motion. The last two equations show how incremental target position angles combine with τ_A and τ_E to provide the total target position angles.

The simulator is composed of two major components: (1) an analog computer that solves all of the equations listed above; (2) a cockpit which includes a display system and the three control elements. The two gun oscilloscope is the pilot's windshield and on it there is displayed a horizontal line for the horizon and a dot for the target. The computer solution for dive angle moves the horizon line up and down. The bank angle causes the horizon line to rotate about the longitudinal axis of the airplane in accordance with the computer solution. Total target position angles τ_A and τ_E control the position of the dot on the scope face.

It is apparent from the block diagram shown in Figure No. 1 that the pilot is an element in the closed loop system. The pilot's input terminals are his eyes and the signal impressed upon the input terminals is the instantaneous target position on the scope. His output terminals are his hands and feet as they affect the stick and rudder controls. Into the closed loop system there is injected the target disturbances $\Delta\tau_A$ and $\Delta\tau_E$. This is analogous to a closed loop mechanical servo system with torque disturbances applied to the load shaft.

Now the problem involved in this project is to find an analytical expression that will describe the pilot's transfer characteristic, i.e., ratio of hand and feet movement to stimulus received at the eyes. It might be argued that the human transfer characteristic could be determined by a much less complicated experiment. This is a subject that lies in the field of psychology[1] and is therefore beyond the scope of this paper. However, intuitive reasoning would indicate that the human pilot, being endowed with intelligence, will tend to shape his transfer function in accordance with environment and a priori knowledge of the components contained in the remainder of the loop. Perhaps it would be more accurate not to refer to the term "transfer function" with its attendant implications of linear operator behavior, but rather to speak in terms of a "descriptive function" for pilot responses. A descriptive function would be an operator, presumably of statistical nature, which would describe input-output relations for human pilots but which would not necessarily be either linear or time invariant.

Mechanization

Four basic mathematical operations are required in order to solve the equations of motion. These operations are:

1. Summation of a number of variables each of which may be multiplied by a constant coefficient.

2. Integration of a number of variables each of which may be multiplied by a constant coefficient.

3. Multiplication of one variable by another.

4. Generation of sine and cosine functions of β .

D-c amplifiers with negative feedback are employed for items 1 and 2. In the case of summation, the input and feedback elements are resistors. For integration, the input elements are resistors and the feedback element is a condenser. The principle of the operational amplifiers used here is described in the literature.[2]

Multiplication of variables is accomplished by the use of a servo. In this case a shaft rotation proportional to one of the variables is produced by the servo. Attached to this shaft is a potentiometer across which is impressed a voltage equal to the second variable. The voltage developed at the wiper of the potentiometer is then proportional to the product of the two variables. In a similar manner, the sine and cosine functions are obtained.

The general philosophy in mechanization is to interconnect the various operational components as directed by the equation. And to start with, one assumes that all the variables on the right hand side of the equation are available. This is illustrated in Figure No. 2 by the mechanization of equation 1. It should be noted that in going through an amplifier a change in sign takes place, thus the second amplifier is required in order to obtain $+\omega_1$. The factor of 10 which multiplies ω_1 is the scale factor chosen for that variable and means that 10 volts will represent one radian per second. Similarly 100 volts will represent one radian so far as δ_a is concerned, etc.

When each of the equations is treated in this manner, all the variables in the system become available. Thus the original assumption about their existence is now a fact. Forty amplifiers and five servo-multipliers are required for the entire mechanization.

Validation

An extensive program was conducted to validate the flight simulator. This was accomplished by introducing step functions in aileron, elevator and rudder one at a time and recording the transient and steady state response for each of the variables. The solutions thus obtained were compared with flight test data and analytical solutions of the mechanized equations. The analytical solutions were simplified by neglecting the cross product terms, i.e. multiplication of one variable by another.

One example of this test is shown in Figure No. 3 for the case of response to a step in aileron. The departure at the origin between simulator solution and flight test data is accounted for by the fact that there was a finite rise time for the step function employed during the flight tests. In general all the computer recordings were in close agreement with flight test data. The flight test data was obtained from the Cornell Aeronautical Laboratory.

Conclusion

Experiments will be conducted with a pilot "flying" the simulator in an attempt to determine his descriptive function in conjunction with the aircraft that is mechanized. This will be done by introducing certain incremental target disturbances as shown in Figure No. 1. The treatment of the data thus obtained and the psychological factors involved in the experiment will be the subject of a future paper.

Acknowledgments

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Bibliography

1. E. S. Krendel, Franklin Institute Laboratories, "A preliminary study of the power spectrum approach to the analysis of perceptual-motor performance", AFTR No. 6723, Wright Air Development Center, October 1951.

2. Ragazzini, Randall, and Russel, "Analysis of problems in dynamics by electronic circuits", Proc. IRE, page 444, May 1947.

EQUATIONS OF MOTION FOR OWN AIRPLANE

$$\omega_1 = \int \left[-50\,\delta_a + 5\,\delta_r + 22\,\psi - 5.5\,\omega_1 + .53\,\omega_3 \right] dt$$

$$\omega_2 = \int \left[-22\,\delta_{el} - 13\,\alpha - 1.6\,\omega_2 - .9\,\dot{\alpha} \right] dt$$

$$\omega_3 = \int \left[-11\,\delta_r + .3\,\delta_a - 15\,\psi - .03\,\omega_1 - .5\,\omega_3 \right] dt$$

$$\psi = \int \left[\omega_3 - \omega_1 \alpha - .2\,\psi - .05\,\mathrm{SIN}\,\beta \right] dt$$

$$\alpha = \int \left[\omega_2 + \omega_1 \psi + .05\,\mathrm{COS}\,\beta - 1.9\,\alpha \right] dt$$

$$\beta = \int \omega_1 \, dt$$

$$\delta = \int \left[\omega_2 \,\mathrm{COS}\,\beta + \omega_3 \,\mathrm{SIN}\,\beta \right] dt$$

TARGET MOTION EQUATIONS

$$V_{AT} = \int \left[-725\,\omega_3 + \omega_1 V_{et} \right] dt$$

$$V_{et} = \int \left[725\,\omega_2 - \omega_1 V_{AT} \right] dt$$

$$\tau_A = \int \left[\omega_3 - \omega_1 \tau_E \frac{-V_{AT}}{3000} - .24\,\psi \right] dt$$

$$\tau_E \int \left[\omega_2 + \omega_1 \tau_A \frac{+V_{ET}}{3000} - .24\,\alpha \right] dt$$

$$\tau_A' = \tau_A + \Delta\tau_A \,\mathrm{COS}\,\beta + \Delta\tau \,\mathrm{SIN}\,\beta$$

$$\tau_E' = \tau_E - \Delta\tau_A \,\mathrm{SIN}\,\beta + \Delta\tau_E \,\mathrm{COS}\,\beta$$

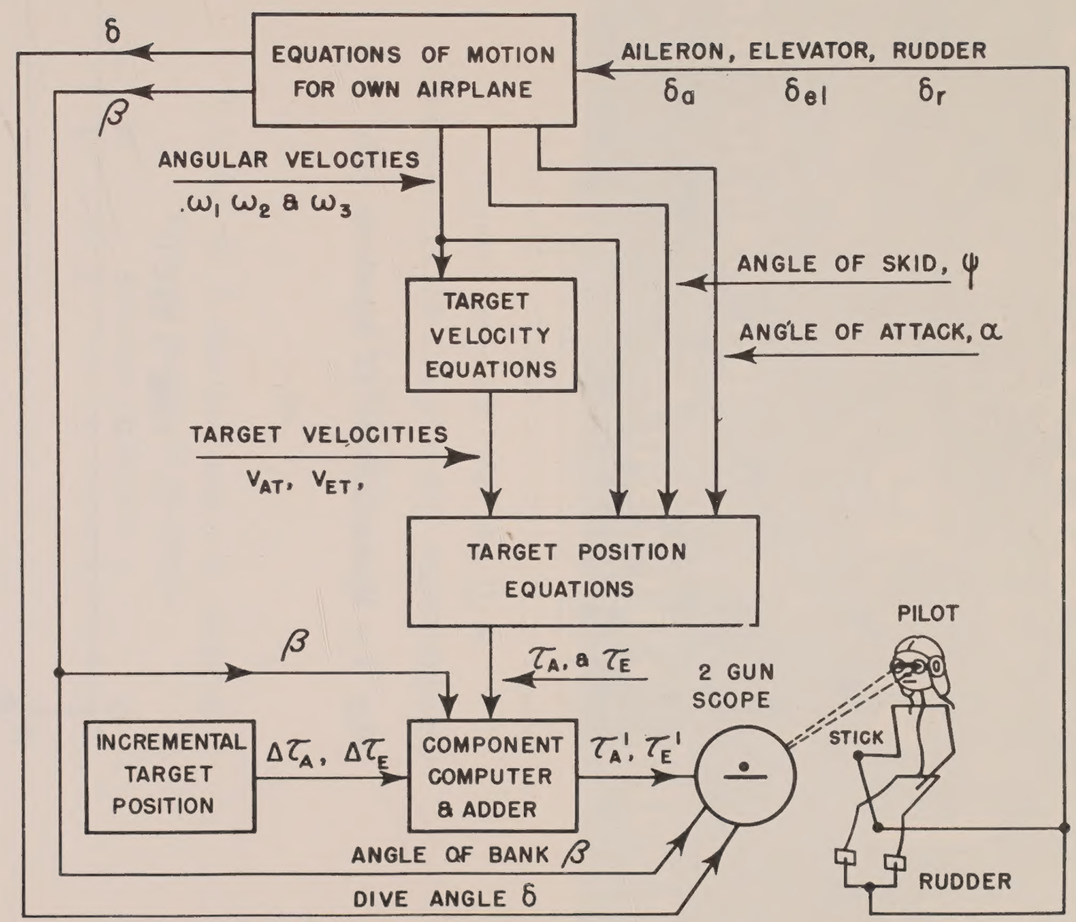

Fig. 1 - Flight simulator (equations and block diagram).

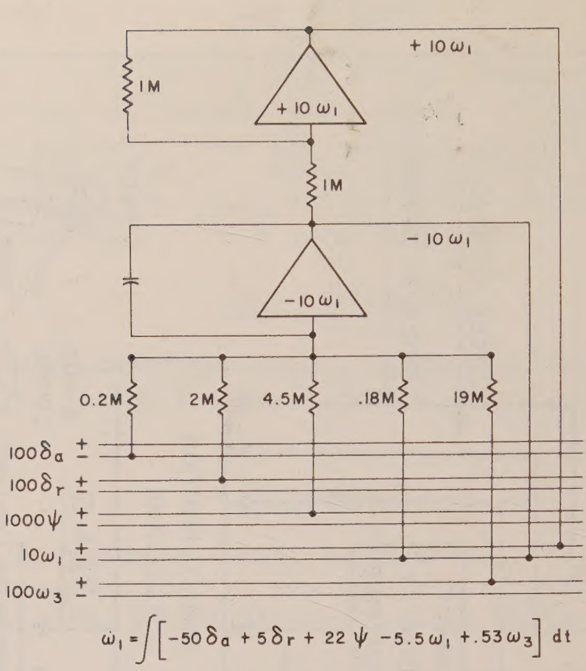

Fig. 2 - Mechanization of equation (1).

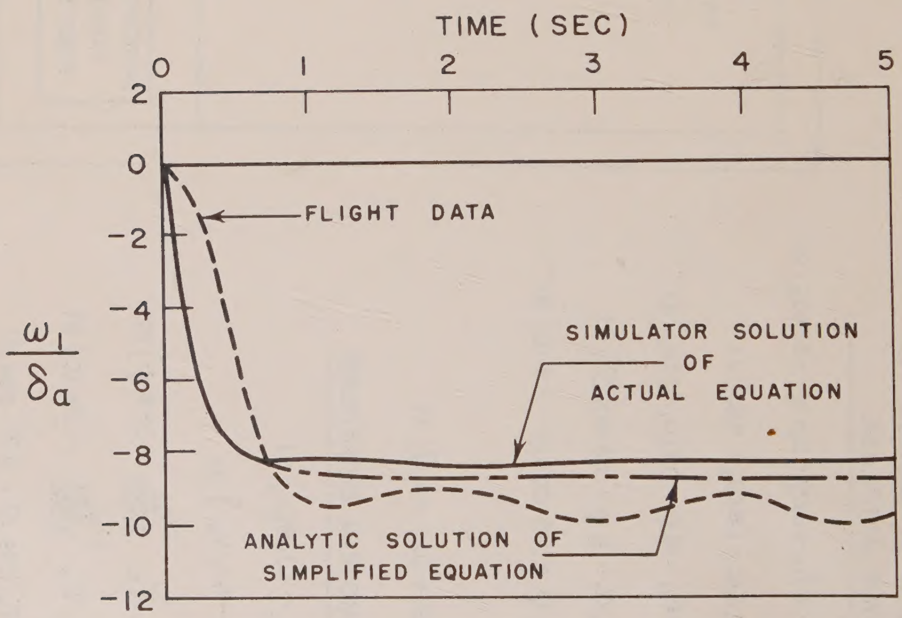

Fig. 3 - ω_1 response for step in aileron.